In a very short time, lasers have advanced from laboratory curiosities to increasingly useful, commercially available tools for material processing, precision measurements, surgery, communication, and even entertainment.

This book provides the background in theoretical physics necessary to understand engineering applications of lasers and optics. It summarizes relevant theories of geometrical optics, physical optics, quantum optics, and laser physics, connecting these theories to applications in such areas as fluid mechanics, combustion, surface analysis, material processing, and laser machining. Discussions of advanced topics such as laser Doppler velocimetry, laser-induced fluorescence, and holography are simplified, yet are sufficiently detailed to enable the reader to evaluate existing systems and design new ones.

The book includes numerous examples and homework problems to illustrate important points. A unique feature is the advanced research problems in each chapter that simulate real-world research and encourage independent reading and analysis.

Engineers and students will find this book a thorough and easy-to-understand source of information.

Introduction to Optics and Lasers in Engineering

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In memory of my dear parents,
Dr. Dov and Shoshana Laufer

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Preface

Over the last two decades, such new technologies as laser-aided material processing, optical communication, holography, and optical measurement techniques have advanced from laboratory curiosities to commercially available engineering tools. Faced with these developments, engineers must now apply in their practice many concepts of physics that in the past were considered outside the boundaries of classical engineering. Advanced levels of electromagnetic theory and of quantum mechanics are now required to answer fundamental questions about interference, diffraction, or polarization of light and their applications. For example: How does radiation interact with gases, liquids, and solids? How does one obtain optical gain? When should a laser be used, and when would an ordinary light source suffice? How can a laser beam be produced and focused? Answers to these questions are essential for selecting an optical technique for measuring the properties of gas, liquid, or solid phases, or when designing a laser system for material processing, surgery, communication, or entertainment. Although most engineering students attend two or three undergraduate courses in physics, they seldom acquire the proficiency required to fully understand the intricacies of modern optics or laser applications. Similarly, midlevel engineers who obtained their formal education before many new techniques were developed may find an increasing gap between the knowledge acquired in undergraduate physics classes and the requirements of professional practice. Because most applications of engineering interest can be analyzed using relatively simple models of the physics of light and lasers, a single course and a single textbook depicting these models and the engineering applications can provide sufficient background for most engineers. Unfortunately, the choice of such textbooks is very limited.

This book was developed to bridge a gap between abstract concepts of physics and practical engineering problems. It summarizes the relevant theories of geometrical optics, physical optics, quantum optics, and laser physics, and connects them to numerous engineering applications. This text navigates the fine line separating extensive descriptions of theoretical physics and the approximate solutions needed for most applications. Relevant theories are described at an advanced level while maintaining a relatively simple mathematical presentation. In addition, an effort was made at each step to elucidate the physical meaning of the mathematical results and the engineering implications. The book has been written primarily for use in graduate courses in mechanical, aerospace, chemical, and nuclear engineering programs. Nevertheless, practicing scientists and engineers in these and other disciplines who are interested in this rapidly developing field should also find the book useful. Owing to the diversity of tasks that these engineering disciplines must face, the scope of the book is broader than that of most engineering optics books. However, with the broad background so provided, it is expected that the reader may successfully follow the advanced research and technical literature in this field.

This book is an outcome of a graduate-level course on laser applications in engineering that I have taught since 1980 and continuously updated. The content, examples, and problems have evolved significantly, with more technical papers reviewed and added to the course, new applications included, many more homework problems developed and solved, and new classroom demonstrations tested. Some recent technical papers became the subject of in-class examples and of homework assignments. Through interaction with students, the methods of presentation were modified and new topics were included to accommodate the needs and the backgrounds of engineering students. I believe that, after a decade of refinement, the contents and format of this text reflect the interests and needs of a large audience.

Although an important objective of the book is to introduce as many applications of engineering interest as possible, it must follow a sequence dictated by the gradually increasing complexity of the physical theories of optics and lasers. Therefore, the organization of the book follows the logical sequence of these theories, which can be effectively divided into four parts: geometrical optics (covered by Chapter 2); physical optics (Chapters 3, 4, 5, 6, and 7); quantum optics (Chapters 8, 9, 10, and 11); and laser physics (Chapters 12 and 13). Accordingly, the discussion of technical applications had to fit into this general structure. Hence, applications that can be explained by the simpler models of geometrical optics are discussed in Chapter 2, whereas discussion of applications requiring more advanced theories such as quantum optics are discussed in later chapters. This is in contrast to most monographs, where applications to one field of engineering are discussed separately from applications to another field. Some of the most important applications are discussed in detail in dedicated sections. Less notable applications are introduced through sample problems or as homework assignments, an attractive approach to engineering students who prefer to solve problems of practical relevance.

The chapter on geometrical optics has two objectives: to demonstrate how simple models can often be used to analyze advanced technical applications,

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and to introduce the concept of ray transfer matrices for the analysis of multi-element optical systems. Since most students are expected to be versed in geometrical optics, simple concepts such as the laws of refraction and reflection or the lens equation are mentioned only in passing. Instead, more involved problems associated with these laws are discussed – for example, propagation through media with continuously varying index of refraction, Fresnel lenses, propagation through multi-element optical systems, and the shadowgraph and schlieren techniques for flow visualization.

The chapters covering physical optics consist of a revision of topics included in undergraduate physics classes. They are distinguishable from similar discussion in standard texts in that they are coupled with related discussions of engineering applications. Chapter 3, on the electromagnetic theory and Maxwell's equations, adds completeness to the book, provides an easy reference, and prevents the use of inconsistent terminology and nomenclature. It is anticipated that most instructors using this book as a text will want to review these topics. The wave equations are derived from Maxwell's equations in Chapter 4, and are solved in one dimension. These results are used in subsequent chapters to explain such phenomena as polarization (Chapter 5), interference (Chapter 6), and diffraction (Chapter 7). Also described are optical devices that rely on these phenomena: polarizers, diffraction gratings, quarter- and half-wave plates, Brewster windows, liquid crystal displays, and more. Examples of technical applications discussed in this part of the book include laser Doppler velocimetry, ellipsometry, interferometry, moiré techniques, and speckle pattern interferometry.

The third part of the book, on quantum optics, provides the link between quantum mechanics and applied optics. Although solutions to problems that involve atomic or molecular systems require abstract mathematical techniques such as operator algebra, most microscopic systems of engineering interest (e.g., the N_2, O_2, H_2O, and CO_2 molecules) have been studied in great detail, and their critical parameters – absorption and emission wavelengths, transition probabilities, and energies of most levels – are tabulated in the literature to a high degree of accuracy. Consequently, most engineers rarely need to derive or measure any of these parameters. They need, rather, to understand the fundamental principles of quantum mechanics, and must acquire the ability to identify and locate the necessary parameters. Therefore, the discussion in this part of the book skips the elaborate mathematical techniques of quantum mechanics while highlighting its physical interpretation. The postulates of quantum mechanics are introduced in Chapter 8, along with the historical background leading to them. Using these postulates, such fundamental observations as the quantization of energy, the probabilistic nature of microscopic systems, and the duality in the representation of waves and matter are presented. This background is sufficient to discuss the structure of single atoms, diatomic molecules, rotational, vibrational, and electronic levels, and the selection rules for single-photon transitions (Chapter 9). The three modes of radiative interaction –

absorption, spontaneous emission, and stimulated emission – are introduced in the following chapter, together with the concepts of line broadening and predissociation. The statistical models for systems in thermodynamic equilibrium are also introduced briefly in Chapter 10, and include (without proof) the equations of blackbody radiation and Boltzmann's distribution. These models allow the reader to connect the behavior of a single molecule or a single atom to the behavior of practical systems containing large numbers of molecules interacting with one another and with a large number of photons. Spectroscopic techniques, which use the effects of blackbody radiation or the equilibrium population distribution for measurements of temperature and species density, are discussed in Chapter 11. Examples include applications of laser-induced fluorescence techniques for gas diagnostics, thermographic phosphor and pressure paint techniques for surface analysis, and more.

The objective of the fourth part of the text is to introduce the fundamental principles of laser oscillators (Chapter 12) and propagation of laser beams (Chapter 13). Just as in the previous chapters, these discussions are coupled with a description of relevant devices and engineering applications. To keep the explanations at a fundamental level, most of the cases described in this section are idealized (e.g., the small-signal gain or the Gaussian distribution of a laser beam); more complex problems (e.g., high-order transverse laser modes) are mentioned only briefly. Nevertheless, even with such a simplified approach, techniques for pulsing laser beams such as Q-switching and mode-locking can be described, along with requirements for successful operation and estimates of pulse duration and pulse power. Similarly good estimates of the geometrical characteristics of a laser beam – for example, the variation of its diameter along the propagation path or its divergence angle – can be obtained from such fundamental analysis. This part is also used to present criteria for successful application of lasers for material processing (e.g., cutting or heat treatment) or for the delivery of laser beams over a long distance (e.g., space communications or distance measurement).

The examples and homework problems in the text were often derived from problems encountered in engineering practice or research. Since the objective of most graduate programs is to prepare students for independent research, I included in each chapter a few research problems, which are a unique feature of the book. To solve them, students must obtain, read independently, analyze, and critically evaluate papers describing various techniques that were not discussed in the book. These problems are intended to simulate real-life research, where earlier results are coupled with existing knowledge to produce new results. All problems in this book – including the research problems – have been solved by my students in previous graduate courses. These students are too numerous to be named individually, but I would like to thank and acknowledge each one of them for their critical review of these problems and for their many helpful suggestions. A special word of appreciation is due to the editors of this book, Florence Padgett and Matt Darnell. Their meticulous work behind the scenes has added much quality to the technical side of the book, its consistency, and appearance. Finally, I would like to thank my dear wife Liora and my children Aharon, Tammar, and Dan. While theirs is not a technical contribution, their love and support were just as essential.